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A REVERSE SHOCK ASSOCIATED WITH A STREAM-STREAM INTERACTION: THE FEBRUARY 29, 1968 EVENT

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Abstract

A clearly defined perpendicular fast reverse shock was found in the interplanetary plasma and magnetic field data from Explorers 33 and 35. An observation by Pioneer 8, which is not unambiguously identifiable because of insufficient data, indicates the evolution of this event. It is suggested that this reverse shock was formed from a stream-stream interaction and that an associated forward shock was developing and probably formed beyond the earth's orbit.

Introduction

The existence of reverse shocks in the solar wind has been suggested by Sonett and Colburn (1965) and Hundhausen and Gentry (1969). Burlaga (1970) first identified a reverse hydromagnetic shock in the solar wind. However, there was no forward shock associated with that reverse shock. Chao et al.(1972) found a reverse shock as part of a shock pair in the solar wind. Recently, Dryer et al. (1972) and Unti and Neugebauer (1972) discussed two reverse shocks.

There are two possible known mechanisms which can generate a reverse shock. Calculations indicate the possibility that a solar disturbance occurring over an extended time ($\gtrsim$ 5 hours) can generate a forward and reverse shock pair observed at 1 AU (Hundhausen and Gentry, 1969). Interaction between streams in the solar wind has been suggested as a mechanism to generate shock pairs by Formisano and Chao (1971) and Hundhausen (1973). Examination of evidence for co-rotating shocks by Ogilvie (1972) suggested a reverse shock, that of September 28, 1967, as the only known likely example.

This paper shows a clearly defined reverse shock which was observed by two spacecraft, Explorers 33 and 35. Furthermore, an observation by Pioneer 8, which is not very distinct because of insufficient data, also suggests the evolution of this shock. In association with this reverse shock a forward pressure pulse, occurring 57 hours earlier, was identified and will be discussed.

Relevant physical parameters and the estimated shock normal and speed will be given for the reverse shock.

Observations

On February 29, 1968 the magnetic field and plasma instruments on board the spacecraft Explorers 33 and 35 measured a discontinuity that we identify as a reverse shock. At the time of the observations, both spacecraft were in front of the earth's bow shock and therefore in interplanetary space. The position of Explorer 33 with respect to earth was (46.8, -52.9, -27.3) R_e in solar ecliptic (X-Y-Z) coordinates and that of Explorer 35 was (61.2, 13.7, 2.5) R_e where R_e(=6378 km) is the earth's radius. Explorers 33 and 35 measured the discontinuity at the times 07 58.0 UT and 07 52.7 UT, respectively. That is, it took about 5.3 min for the discontinuity to travel from the position of Explorer 35 to that of Explorer 33. In considering the gross features of plasma and magnetic field variation, we divide the region of the pressure build-up by the velocity gradient into four parts as shown in Figure 1. The dividing lines are marked by the letters A, B, C, D and E which are characterized by a discontinuity at each of these times. The figure shows the total pressure defined by $P = B^2/8\pi + Nk(T_e + T)$, with the assumption that the most probable electron temperature is $T_e = 1.5 \times 10^5$ °K. Also shown are the proton temperature T, the proton number density N, the plasma bulk speed V, and the magnetic field intensity B, for an 88-hour period associated with the event. The pressure decreased by nearly a factor of 4 across the shock discontinuity on February 29 which excludes the possibility of it having been a tangential discontinuity.

Figure 2 shows (81 sec) averaged magnetic field and detailed plasma data from Explorers 33 and 35, respectively, at the time of the shock passage. All velocities in this paper are given in a nonrotating frame of reference (aberration removed), fixed with respect to the sun and centered at the spacecraft of interest. We see a discontinuous decrease in N, proton thermal speed U_{TH}, and B, while V increases. Such a signature certainly has the appearance of a reverse shock. The cross-points are the measurements of Explorer 35 and the dot-points are those of Explorer 33. For the field data only every other 81 sec average was plotted. The gaps occur when there were no data available. The infrequently sampled plasma (approximately one every 2.5 min) and the averaged magnetic field give the appearance of a broad shock. However, the data-listing of the detailed field shows that the shock jump occurred within the magnetometer sampling time, i.e. 5.11 sec.

About five and a half hours, or 352 minutes, later when Pioneer 8 was at the position (-1000,785,21) R_e in solar ecliptic coordinates, the field instrument on that spacecraft measured changes in the magnetic field intensity which gave a profile similar in gross features to that measured by the instruments on 33 and 35; the dashed curve in panel 4 of Figure 1 shows a plot of the field strength for Pioneer 8's location. In order to show that the events observed at Pioneer 8 and Explorer 33 generally correspond to each other, Pioneer 8 measurements have been shifted in time about 4.4 hours so that the events are simultaneous in the figure. The field magnitudes on each side of the discontinuity at Pioneer 8 at $\approx$1230 UT equal those measured at Explorer 33 at 0758 UT within the accuracy of the measurements. However, there are important detailed differences between the two sets of data which now will be discussed.

Higher resolution magnetic field data measured by the magnetic field instrument on Pioneer 8 as given in Figure 3 show this difference from the data measured near the earth. There is a jump in B within the data sampling time of 5.11 sec with well-defined up and down-stream states across the reverse shock at the Explorer 33 position, but this signature was not found at Pioneer 8. The change in field magnitude as observed at ≈1230 UT at Pioneer 8 is much broader than that observed near the earth. We tentatively identify this boundary as a piston which drove a shock propagating away from it. The large amplitude pulse at approximately 1345 UT may correspond to a nonlinear wave which behaved more like a shock wave when it was closer to the driving piston as observed earlier by the two Explorers.

Table 1 gives the values of the averaged plasma and magnetic field measurements and their RMS deviations for the Explorers 33 and 35 data, pre- and post-shock. The length of the time intervals used for calculating the averages are shown in Figure 2 as horizontal arrows; the figure caption defines the quantities in the Table where 1 refers to the up-stream (undisturbed) region and 2 to the downstream (disturbed) region of the shock, and $\vec{W} = \vec{V}_2 - \vec{V}_1$. The values in Table 1 will be used to test the validity of the assumption that the discontinuity on February 29 was an MHD reverse shock and to compute other physical quantities for this reverse shock.

The appropriate time intervals for calculating the averages were based on the steadiness of the quantities. Plasma data intervals were taken longer than 20 minutes for the averages, but the corresponding magnetic field data intervals were taken shorter than 5 minutes. Only the values of the magnetic field in the vicinity of the shock discontinuity were used to represent the up- and down-stream values of the shock. Giving a justification for using different plasma and field averages is difficult. However, for frequencies of 0.01 Hz or lower, it is well known that the magnetic field usually fluctuates more rapidly in the solar wind than the plasma quantities (Belcher, 1973), and around shock discontinuities the field usually responds more rapidly to the total pressure change than do the plasma quantities.

TABLE 1

AVERAGE VALUES BEFORE AND AFTER SHOCK DISCONTINUITY

Parameter	Explorer 33 Average	Explorer 33 ± error (σ)	Explorer 35 Average	Explorer 35 ± error (σ)
B_1 (γ)	6.5	0.2	5.7	0.1
B_2	9.5	0.8	10.1	0.5
V_1 (km/sec)	479	17	477	9
V_2	425	10	400	12
N_1 (#/c.c)	3.3	0.3	3.2	0.3
N_2	6.1	0.6	6.9	0.7
θ_{B1}	-20.0°	4.5°	-1.5°	1.1°
Φ_{B1}	292.7°	5.6°	282.0°	6.7°
θ_{B2}	-28.0°	3.0°	-4.5°	1.0°
Φ_{B2}	300.5°	9.5°	280.0°	4.0°
θ_{V1}	-1.9°	2.0°	-2.1°	0.2°
Φ_{V1}	182.8°	2.5°	181.3°	2.5°
θ_{V2}	-3.7°	1.3°	-8.5°	2.4°
Φ_{V2}	177.5°	2.6°	178.3°	1.4°
W_x (km/sec)	59	16	90	12
W_y	42	16	22	21
W_z	-11	22	-41	23

Analysis of Explorer Data

First, we have shown (see Figure 1) that discontinuity E could not have been a tangential discontinuity because the total pressure P dropped by a factor of about 4 across the discontinuity. The composite signature of the changes in B, N, T, and V was that of a reverse shock. The magnetic field direction did not change appreciably across the discontinuity. In fact, if we neglect the fluctuations in θ within 2 minutes of the discontinuity, especially in the case of the Explorer 35 measurements, then the change in direction of $\vec{B}$ across the discontinuity from one steady state to the next was approximately 4°; the corresponding directional change of $\vec{B}$ for the Explorer 33 case was about 11°. In any case, it is clear that the average magnetic field vectors on each side of the shock were almost parallel for both sets of spacecraft observations. Hence, the magnetic coplanarity theorem cannot be used to find the shock normal direction, and therefore the best-fit technique of Lepping and Argentiero (1971), which depends in part on this theorem, does not apply.

In accordance with the MHD shock relations for a <u>normal</u> shock the following three conditions were fulfilled for the Explorer observations. First, the magnetic field direction did not change across the shock but its magnitude changed significantly. Second, the bulk velocity difference vector $\vec{W}$ of the solar wind was almost perpendicular to $\vec{B}_1$ and $\vec{B}_2$. Third, the ratio of number densities was nearly equal to the ratio of magnetic field magnitudes across the shock ($B_2/B_1 \approx N_2/N_1$). The first condition is apparent from Figure 2 and the second and third conditions, within the uncertainty of the measurements, are demonstrated by the results shown

TABLE 2

TEST OF NORMAL SHOCK CONDITIONS

	$\measuredangle(\vec{B}_1, \vec{B}_2)$	$\measuredangle(\vec{B}_1, \vec{W})$	N_2/N_1	B_2/B_1
Explorer 33	$11^\circ \pm 12^\circ$	$81^\circ \pm 10^\circ$	1.8 ± 0.4	1.5 ± 0.1
Explorer 35	$4^\circ \pm 7^\circ$	$89^\circ \pm 10^\circ$	2.1 ± 0.4	1.8 ± 0.1

in Table 2. Since the normal shock conditions are demonstrated, then the shock normal must have been in the same direction as $\vec{W}$ or perpendicular to $\vec{B}_1$ (or to $\vec{B}_2$) within $\approx \pm 10^{\circ}$.

<u>Normal Shock Approximation</u>

Using the shock normal and speed determined from the data of both Explorers 33 and 35 independently, the delay time for the shock to propagate between the positions of the two spacecraft was computed and agreed with the observed value (5.3 min.). This same combination of shock normal and speed from Explorers 33 and 35 was also used to check the time of occurrence of the <u>pulse</u> (at 1345 UT) in the magnetic field data observed by Pioneer 8. The computed transit time (290 ± 50 min) for the shock to propagate from the Explorer positions to Pioneer 8 was consistent with the measured value (352 min).

Concerning the uncertainties of the shock normal and speed, the standard deviations of the measured quantities were used to generate the error cone of the shock normal independently for each set of observations. Multiple spacecraft observations were also used to minimize the error cone of the shock's normal and the uncertainty of its speed. Thus, the multiple spacecraft observations not only were used to check the shock normal and speed determined from the single spacecraft computation, but also were used to improve their accuracy as well. Table 3 summarizes the results of the computations of the relevant speeds.

Table 4 gives the estimated shock normal ($\hat{n}$) and shock speed and their uncertainties, which are consistent with all the observations, and presents other relevant physical quantities, where the calculation of V_A

TABLE 3

ESTIMATES OF V_S

Source of Computation	Observed T(min)	V_S(km/sec)
$\vec{W}$ from Explorer 34 data, 35-normal, and mass conservation equation		230
$\vec{W}$ from Explorer 33 data, 35 -normal, and mass conservation equation		280
$\dfrac{\Delta\vec{R}_{33-35} \cdot \hat{n}_{35}}{\tau_{33-35}}$	5.3	350
$\dfrac{\Delta\vec{R}_{33-8} \cdot \hat{n}_{35}}{\tau_{33-8}}$	352	250
	Average V_s ($\pm\sigma$) =	280 ($\pm$50)

TABLE 4

SHOCK NORMAL AND SPEED

Shock normal, $\hat{n}$	
(θ_s, Φ_s) and (n_x, n_y, n_z)	$(24^{\circ}, 194^{\circ})$ $(-0.89, -0.22, 0.41)$ with $\varepsilon = 7^{\circ}$
Shock Speed, V_s (km/sec)	280 ± 50

PHYSICAL QUANTITIES REFERENCED TO THE SHOCK FRAME

V_A, Alfven Speed (km/sec)	74 ± 4
V_F, fast wave speed (km/sec)	92 ± 10
M_F, fast Mach number	1.4 ± 0.2
T_{e1} (computed) (^{o}K)	$(4 \pm 2) \times 10^5$
T_{e2} (computed) (^{o}K)	$(6 \pm 2) \times 10^5$
T_{e2}/T_{e1} (computed)	2.5 ± 1.5
T_{p2}/T_{p1} (measured)	1.7 ± 0.5

was based on B_1. The true shock normal is estimated to be located in a cone whose axis is directed along (θ_s, Φ_s) and such that the half angle of the cone, ϵ, gives the (95%) probable error in $\hat{n}$. It is noted that the MHD shock conservation equations, including the energy equation, are satisfied with the average observed quantities and the estimated normal.

This discontinuity apparently propagated at a nearly constant speed and direction on a scale of the separation between the earth and Pioneer 8 of the order of 1/30 AU, having shock characteristics at the Explorers and evolving to a nonlinear wave (pulse) at Pioneer 8.

Formation of the Reverse Shock

The overall enhanced strength of P, B, N and T, as shown in Figure 1, are due to the gradients in the bulk speed V. It was suggested by Formisano and Chao (1971) and Hundhausen (1973) that a pressure pulse can be built up by a gradual velocity gradient caused by a fast stream overtaking a slow stream. When it is strong enough, this pressure pulse, driven by the stream-stream interaction, may act as a double piston to push "backward" and "forward" producing a forward and reverse shock combination.

In this figure as mentioned above the gross plasma and field changes disclose discontinuities at the times A, B, C, D, and E. We have shown that discontinuity E corresponds to a reverse shock. Across discontinuity A, the pressure was also not balanced, which excludes the possibility of a tangential discontinuity having occurred there. However, it was also not a shock wave because the signature of the plasma and magnetic field profile was inconsistent with that of a shock. It is suggested that the pressure discontinuity A may have eventually developed into a forward shock. We also suggest that B and D, which were tangential, correspond to discontinuities where the reverse shock and the discontinuity A originated. Discontinuity C may be a contact discontinuity as suggested by Razdan et al. (1965) and Sonett and Colburn (1965). The same type of gross profile occurred before the reverse shock discussed by Burlaga (1970), the September 28, 1967 event, where again the forward shock was not well developed. Hundhausen (1973) also suggested, from numerical computations, that a velocity gradient can produce a shock pair <u>beyond</u> the earth's orbit.

Summary and Discussion

A reverse perpendicular shock was observed by Explorer 35 at the time 0752.7 UT on February 29, 1968. Then 5.3 minutes later Explorer 33 observed a nearly perpendicular reverse shock. The magnetic field profile was not entirely the same at these two points of observation. There were fluctuations in the vicinity of the discontinuity. Explorer 35 saw a fluctuation in the latitude angle θ within 2 minutes behind the shock, Such a fluctuation does not occur in the data of Explorer 33. However, for the analysis intervals shown in Figure 2 (which reasonably indicate the pre- and post-shock states) the change in the magnetic field direction across the shock discontinuity at Explorer 33 is larger than that of the shock discontinuity at Explorer 35. Hence, the perpendicular shock approximation should be better for the Explorer 35 data. The computed transit time agrees very well with that measured for the shock propagating from Explorer 35 to 33.

A tentative identification of the event at the Pioneer 8 position, which was about 1000 R_e behind earth's orbit, was made (see field intensity B, dashed curve, in Figure 1). At that location the gross variation of the magnetic field strength was similar to that of Explorers 33 and 35. A detailed examination of Pioneer 8 data (See Figure 3) indicates that a large amplitude pulse propagated away from the compressed higher field region. Because no plasma data was available for the Pioneer 8 observation, a definitive identification of this pulse as the reverse shock is not possible

We hypothesize that this reverse shock was formed from a stream-stream interaction. The shock normal's azimuthal angle, $\Phi_s = 194^{\circ}$, gives support to such a mechanism; the ideal direction would be 225° ($=315^{\circ}-90^{\circ}$). For more than 3 days before and after the shock the angle $\langle\Phi_B\rangle$ from the hourly averaged magnetic field was $\approx 315^{\circ}$ (see Mariani et al., 1971). As Table 1 shows $\langle\Phi_B\rangle$ just before the shock was 282°, which is orthogonal to $\Phi_s = 194^{\circ}$ within 2°. A high probability of occurrence of perpendicular reverse shocks with respect to all reverse shocks in the solar wind should be expected due to the operation of the stream-stream mechanism and the high expectation of the undisturbed magnetic field being directed along or near, the ideal spiral direction. The reverse shocks studied by Burlaga (1970) and Unti and Neugebauer (1972) were also perpendicular shocks.

It is expected that a forward shock was developing and probably formed beyond the earth's orbit. This picture is consistent with Burlaga's (1970) suggestion that the reverse shock formed at the boundary between a "driver-gas" and a "driven gas". We suggest further the likelihood that beyond the earth's orbit a shock-pair eventually formed and separated the "driver" and "driven" gas. This shock-pair would have a separation on the order of that consistent with the interval between A and E in Figure 1, 57 hours, if the forward shock formation occurred just beyond earth's orbit. For $V_1 \approx 480$ km/sec this separation would be ≈ 0.7 AU.

Acknowledgement

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Figure Captions

Figure 1 Averaged data (15 min/ave) from Explorer 33 showing: T, the proton temperature; N, the proton number density; V, the bulk solar wind speed; B, the field magnitude; and P, the total pressure (see text). The curves for Explorer 35 are similar. The dashed curve in panel 4 is a plot of 15 min averages of B for the Pioneer 8 data, shifted to an earlier time by 4.4 hours.

Figure 2 Superimposed plasma and averaged magnetic field data for the Explorer observations. U_{TH} is the thermal velocity $\left(= \sqrt{2Tk/m_p}\right)$, V is the proton bulk speed and Φ_V and θ_V indicate the flow direction (θ_V is inclination from the ecliptic plane measured positive "northward" and Φ_V is azimuthal angle with $\Phi_V = 0^o$ in antisolar direction). N is the proton number density. B is the magnitude of the magnetic field and Φ_B and θ_B indicate its direction (θ_B is measured the same as θ_V and $\Phi_B = 0^o$ in solar direction). The Explorer 35 curve was shifted 5.3 minutes to match the Explorer 33 shock discontinuity. Horizontal arrows indicate the analysis intervals.

Figure 3 A profile of the magnetic field magnitude at Pioneer 8 showing a pulse at 1345 UT, ≈ 5-1/2 hours after the reverse shock passed the Explorers.

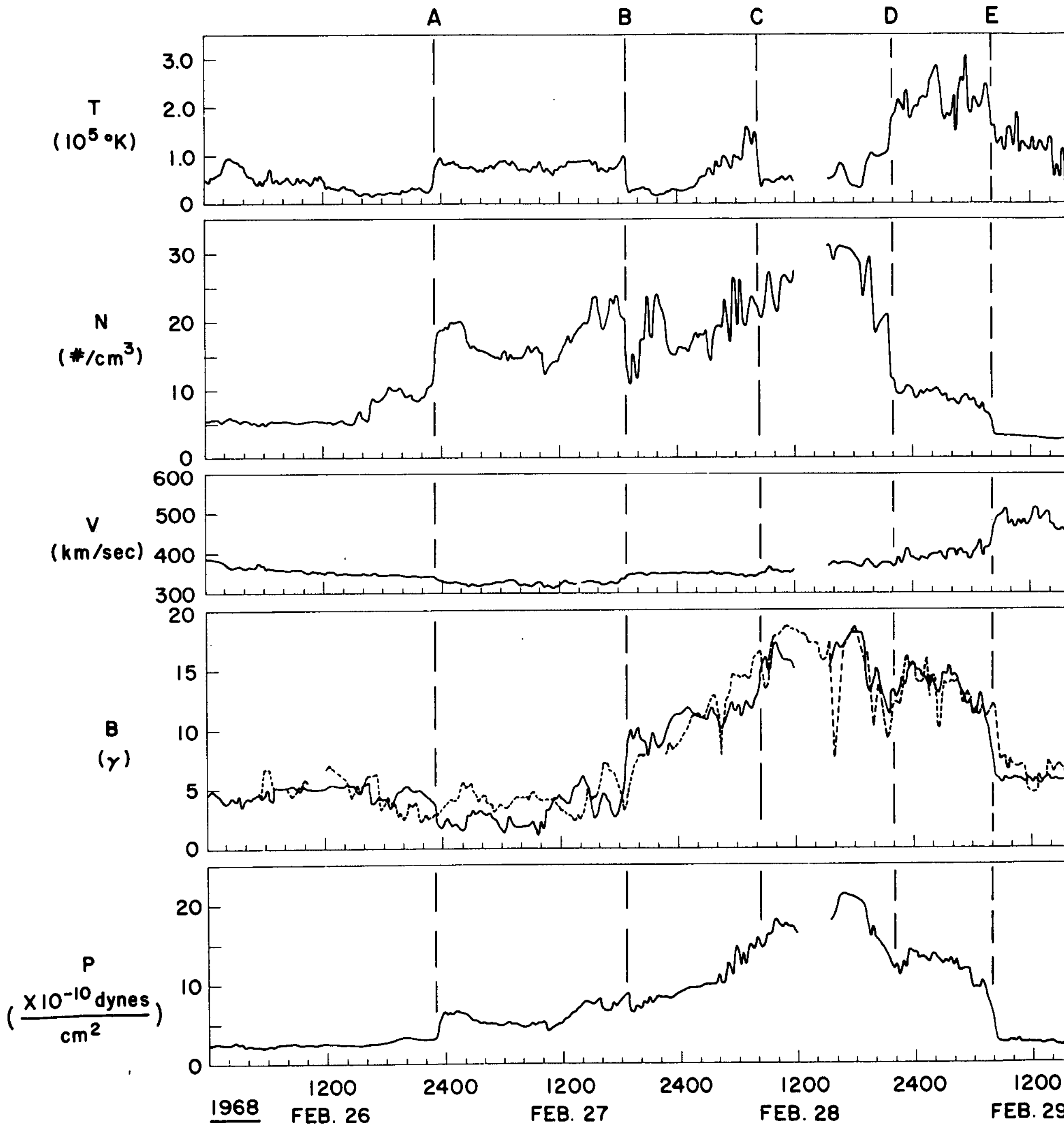
A
B
C
D
E
T
(10^5 °K)
3.0
2.0
1.0
0
N
(#/cm^3)
30
20
10
0
V
(km/sec)
600
500
400
300
B
(γ)
20
15
10
5
0
P
($\frac{X10^{-10} dynes}{cm^2}$)
20
10
0
1200
2400
1200
2400
1200
2400
1200
1968
FEB. 26
FEB. 27
FEB. 28
FEB. 29

FIGURE 1

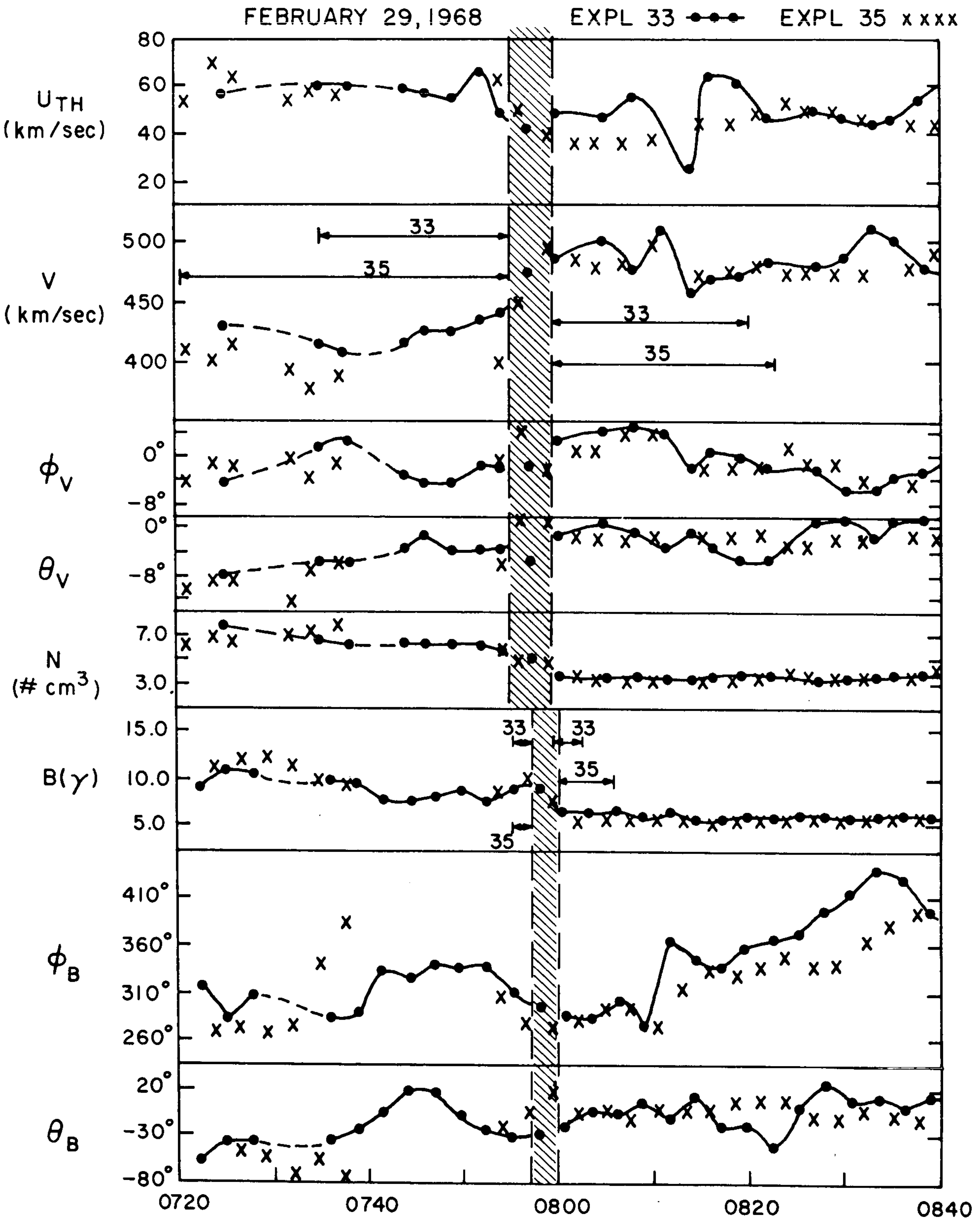
FEBRUARY 29, 1968
EXPL 33
EXPL 35 x x x x
U_{TH} (km/sec)
V (km/sec)
ϕ_V
θ_V
N (# cm^3)
B(γ)
ϕ_B
θ_B
UT (AT EXPL 33)

FIGURE 2

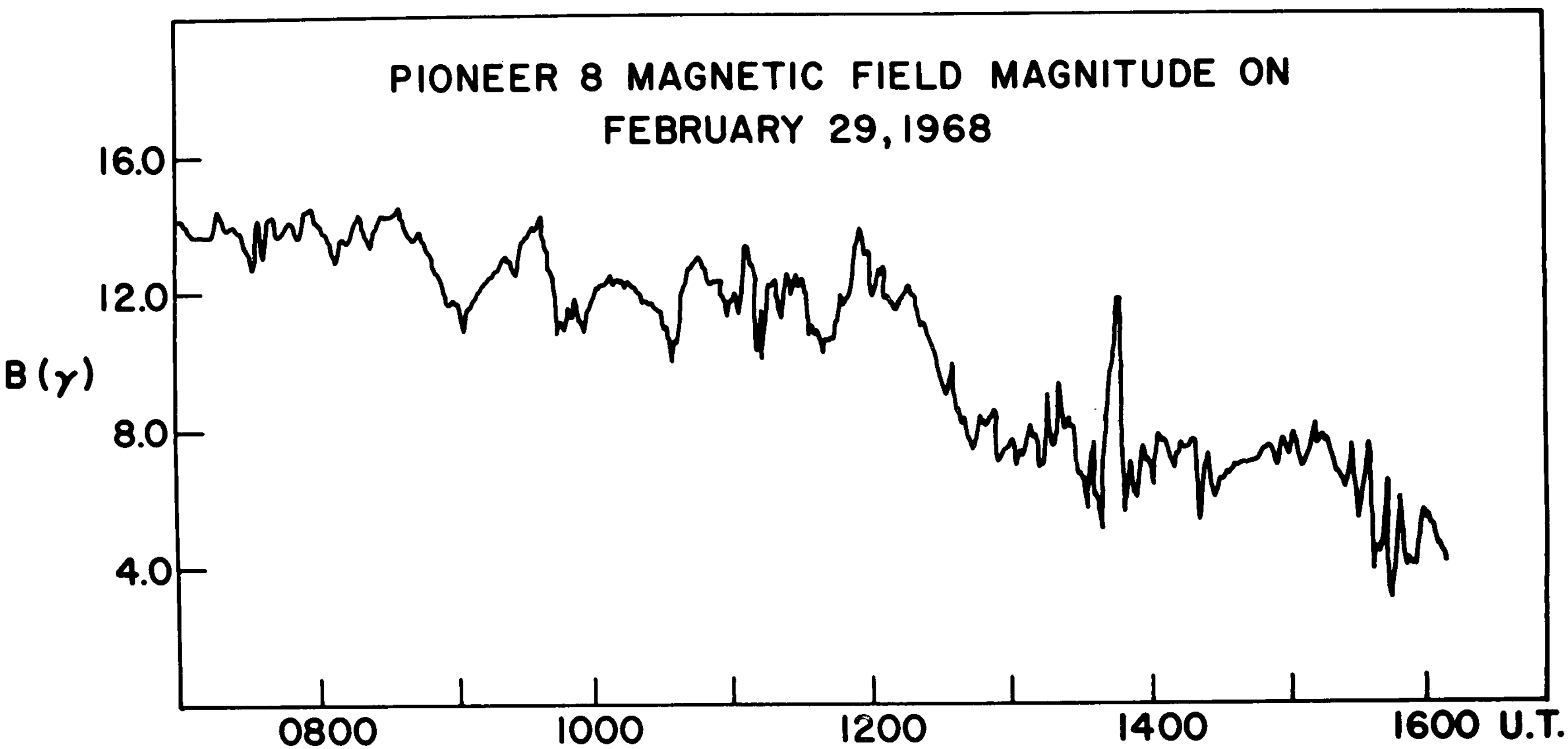

FIGURE 3

* U.S. GOVERNMENT PRINTING OFFICE: 1973—734-723/118